Recent Silicon Carbide Optical Performance Results at SSG/Tinsley

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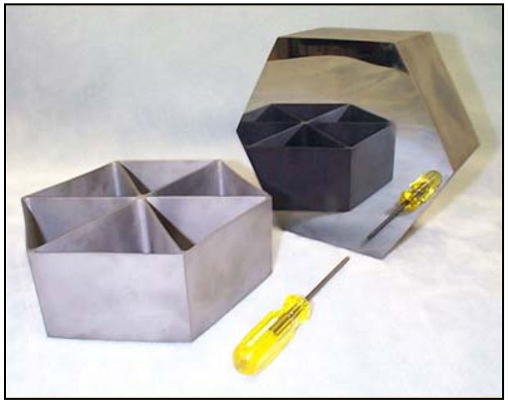
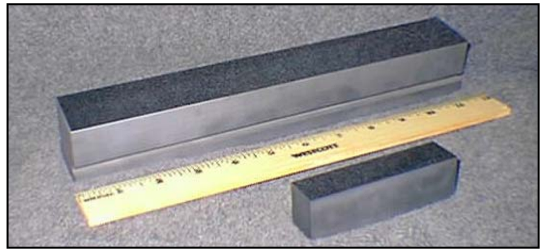
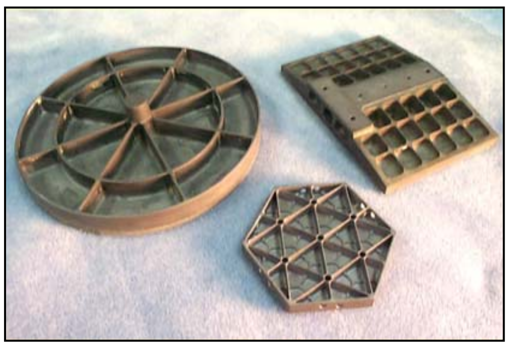
Overview

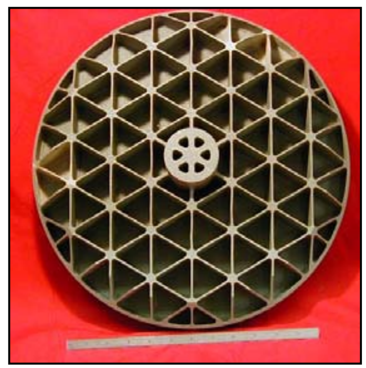
- Several activities ongoing at SSG and Tinsley to improve (1) SiC substrate manufacturing capability, (2) Optical performance obtained with SiC optics, and (3) Speed of optical polishing/finishing associated with SiC optics
  - Substrate Manufacturing Improvements:
    - Focused on simplifying the attachment schemes required for SiC system integration
  - Optical Performance Improvements:
    - Variations in manufacturing process flow and the application of Tinsley's proprietary Computer Controlled Optical Surfacing (CCOS) result in significant improvements in the optical quality demonstrated in SiC optics
      - Recent silicon clad SiC optics results
      - CVD SiC clad SiC results
  - Development activities focused on improving speed of SiC optical fabrication:
    - "Blending" demonstrations show a path to multiple head CCOS machine configuration
    - In-situ tool dressing demonstrated to improve uniformity of material removal, critical to improving convergence for hard materials

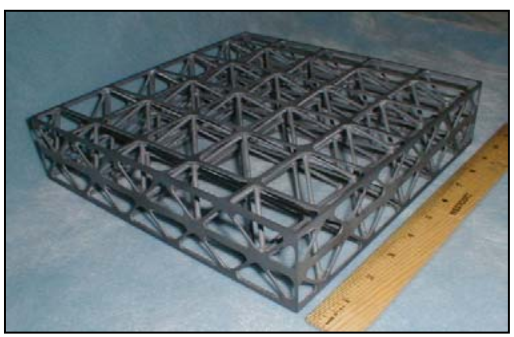
SiC Substrate Manufacturing – Reaction Bonded Silicon Carbide

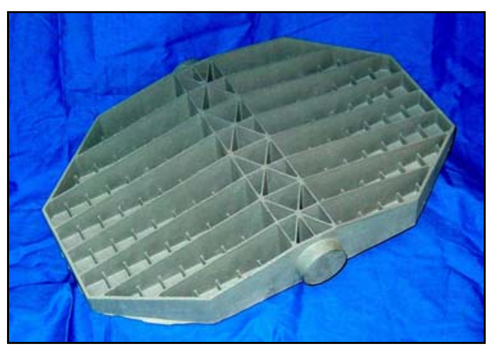


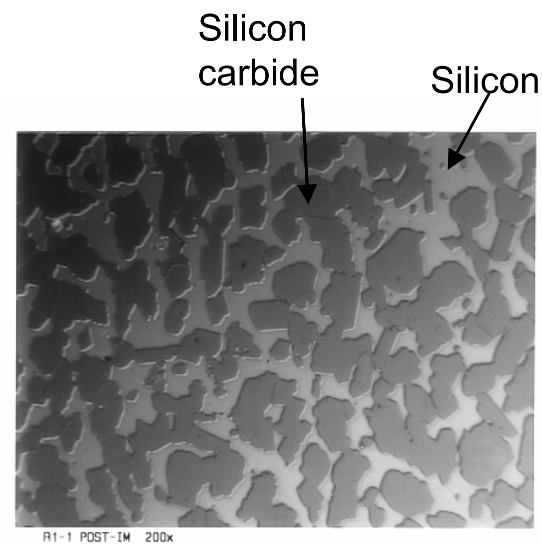












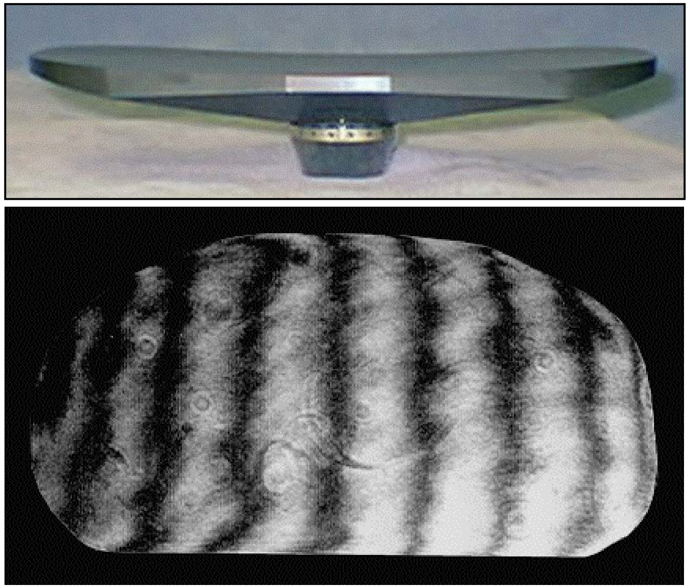
RB SiC Microstructure

- Reaction Bonded slip casting fabrication process allows intricate, stiff, monolithic structures to be produced with little to no post machining

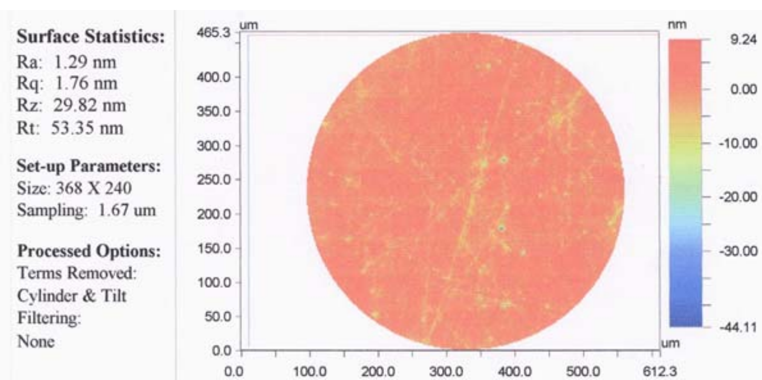
Substrate Manufacturing Improvements

- NASA contract NAS8-01085, *SiC Lasercom Telescope with Automated Mirror Figuring* (NASA COTR: Dr. Andrew Keys), offered opportunity to develop SiC figuring processes.
- New design and manufacturing methodology demonstrated to facilitate SiC optical system integration, minimize invar, and reduce weight.
  - Traditional SiC integration approaches rely on metallic interface inserts which are epoxy bonded or brazed into the SiC components.
  - Process developed and demonstrated uses the material properties of the SiC to allow attachment of SiC components directly to one another.
  - Number of SiC components minimized by sinter joining parts to obtain a monolithic metering structure.

Silicon Clad SiC Asphere Optical Performance (Traditional Optical Processing)



ALI Primary Mirror (spare) Surface Figure (< 150 nm pk-valley)

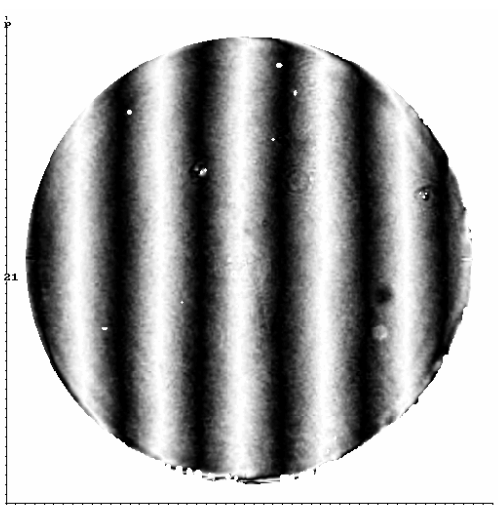


ALI Primary Mirror (spare) Surface Finish (18 Angstroms RMS)

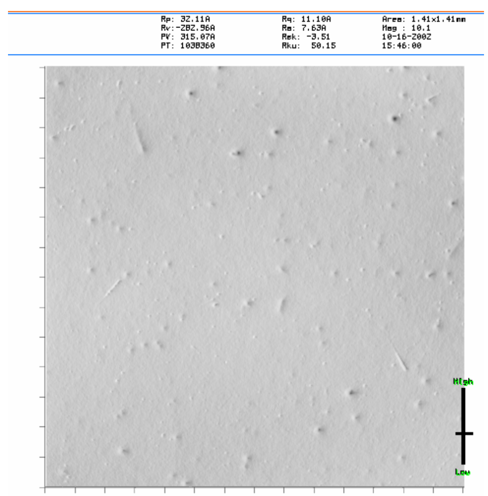
- Traditional fabrication process flow demonstrated to provide visible quality surface figures and microroughness/stray-light characteristics suitable for stressing earth observing applications
- EO1 Technology Demonstration Optics Results shown
  - Primary Specifications:
    - Off Axis general asphere (~165 cm base radius of curvature)
    - 33 cm x 17 cm clear aperture
    - Surface Figure < 150 nm pk-valley
    - Surface Finish < 20 Angstroms RMS

CCOS Polished Silicon Clad RB SiC Mirror Results (1 of 2)

- Tinsley's CCOS process provides significant improvements in optical quality
- 29.5 cm diameter
- Off-axis parabola
- Surface Figure: 8 nm RMS
- Surface Finish 8 – 15 Angstroms RMS



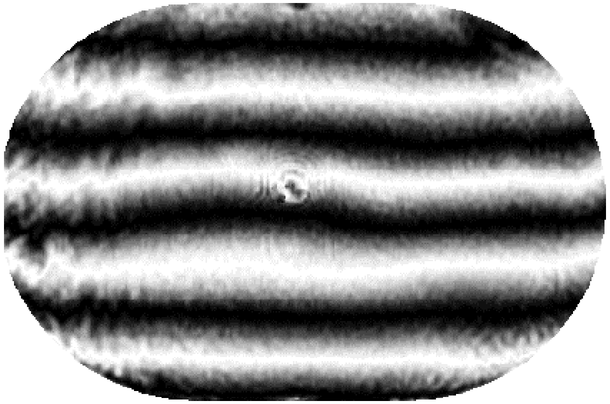
8 nm rms surface error



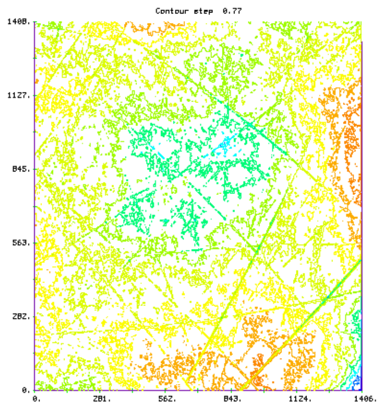
8-15 angstroms rms surface roughness

CCOS Polished Silicon Clad RB SiC Mirror Results (2 of 2)

- Tinsley's CCOS process provides significant improvements in optical quality
- 22 cm x 14 cm
- Off-axis parabola
- Surface Figure: 11 nm RMS
- Surface Finish 9 Angstroms RMS



0.0167 λ rms surface figure



9 angstrom rms
surface roughness

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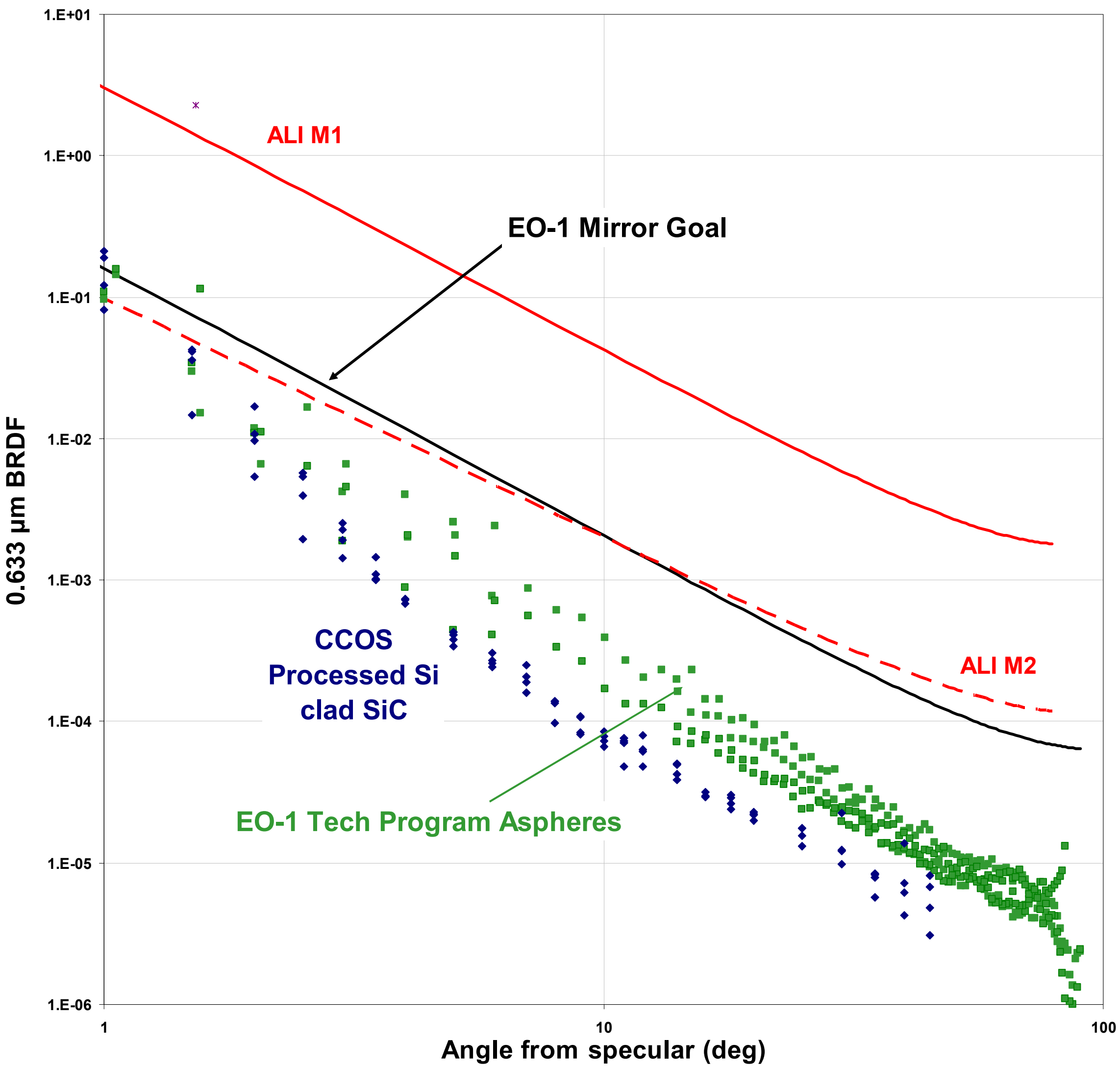
CCOS Processed Silicon Clad SiC Asphere BRDF



- **CCOS Polished Silicon clad SiC Asphere BRDF**
- Silicon clad BRDF demonstrated on EO-1 technology program exceeded ALI program requirements
  - as much as 10x
- CCOS polished silicon cladding demonstrates further improvement in BRDF
  - Another factor of 6x

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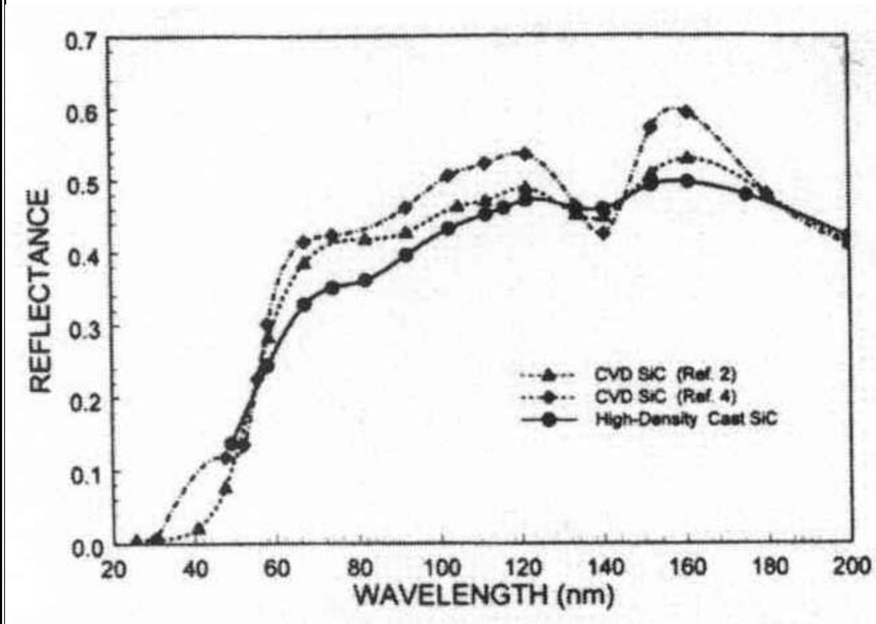
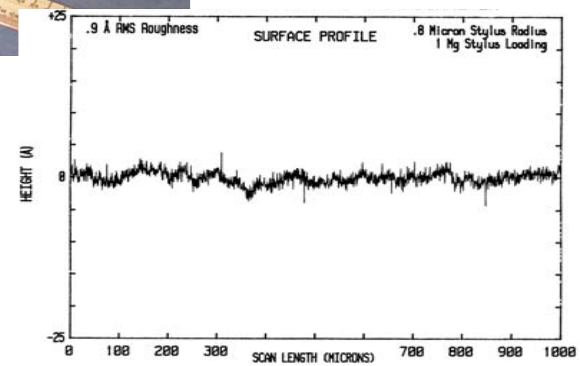
CCOS Process Capability Facilitates Aspheric Optical Manufacturing Directly in the SiC Material

- Traditionally, aspheric processing of SiC coatings and/or substrates not practical
  - Single point diamond turning cannot be applied due to hard/brittle nature of SiC material
  - Traditional aspheric optical finishing approaches are not practical due to the materials low removal rate
- CCOS processing obviates both of these concerns
  - Deterministic CCOS grind process is suitable for brittle SiC materials, eliminating the need for SPDT
  - Automated CCOS polish process eliminates the need for hand-figuring to final figure/finish making the slow material removal rate of the SiC material a manageable issue

Potential Benefits of CCOS Processed SiC Aspheric Optics



Uncoated SiC Demonstrates High EUV Reflectivity

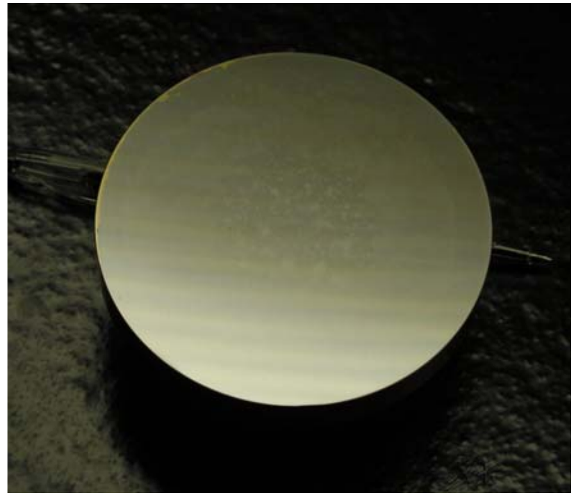


CVD Clad RB SiC Mirror Microroughness: 0.7 – 1.4 Angstroms RMS

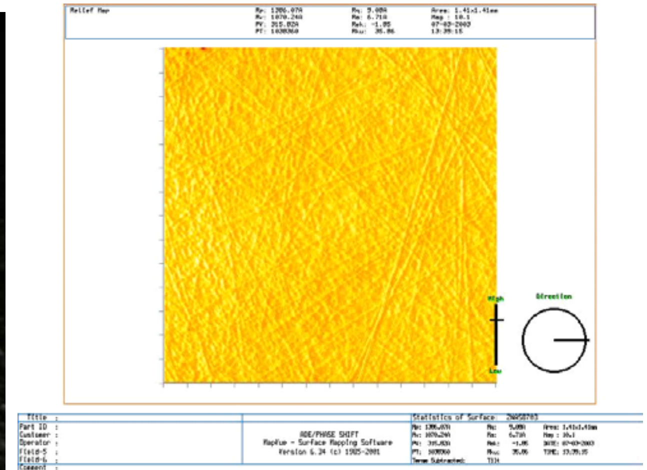
- Eliminates need for thick silicon cladding deposition
- Allows improved microroughness/BRDF
  - CVD SiC clad RB SiC mirrors demonstrated to support ~ 1 Angstrom RMS microroughness
- Allows improved reflectivity over EUV spectrum
  - CVD and Cast SiC substrates demonstrated to have high reflectivity over EUV waveband (60 – 200 nm)

EUV Phase I Results

RB SiC Mirror Substrate



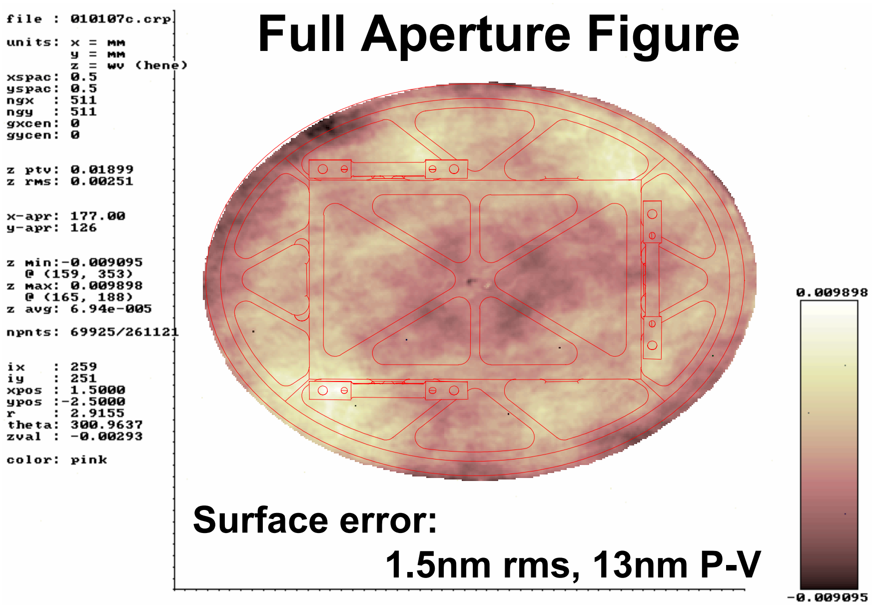
Non-Uniform CVD SiC Cladding

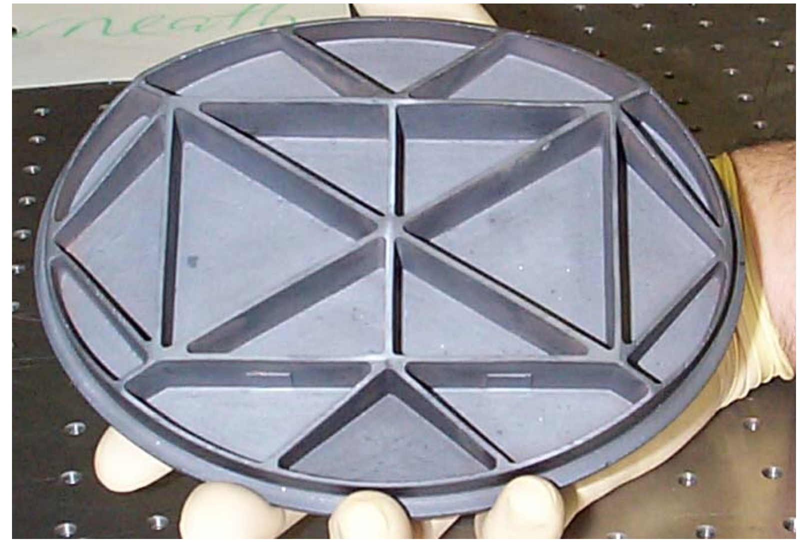


10 Angstroms RMS Microroughness Demonstrated

- Phase I SBIR contract with NASA/GSFC in place to try to demonstrate ability of CVD SiC clad SiC optics to meet EUV quality requirements utilizing a process flow suitable for aspheric optics fab
- NASA contract # NAS5-03039
  - Dave Content TPOC
- Several coating runs made on RB SiC mirror substrates
  - 100 mm diameter spherical substrates
  - CCOS processed consistent with aspheric mirror polishing processes
  - Some runs delaminated due to poor surface preparation
  - Best results obtained with a non-uniform coating run which gave reasonable results in some sub-apertures
  - 10 Angstroms RMS surface roughness demonstrated

CVD clad RB SiC Fold Flat





- SiC Fold Flat Produced
  - 180 mm x 125 mm
- CVD cladding and CCOS polish processes applied to achieve final surface figure/finish
  - Process consistent with aspheric optical fabrication
  - Figure: 1.5 nm RMS; 13 nm pk-valley
  - Finish: 9 – 13 Angstroms RMS
    - Better than requirements, better results could have been achieved

Development Efforts Focused on Rapid SiC Mirror Fab

- Slip cast substrate manufacturing process is fast and cost effective
- Rapid SiC mirror production will require Improvements in the efficiency/convergence associated with the polishing process
  - CCOS grind/polish with multiple, simultaneous spindles
    - An approach for blending of these different polishing regions has been developed and demonstrated
      - DARPA Contract # DAAH01-03-C-R067
      - TPOC: Dr. Rob Hauge, Darpa Program Manager
  - In-situ tool dressing can be applied to improve tool material removal rate variation as a function of time
    - More uniform tool characteristics result in better surface convergence
      - NASA Contract # NAS8-03036
      - TPOC: Dr. Phil Stahl, NASA/MSFC

Summary

- Improvements in a number of SiC mirror manufacturing areas ongoing
  - Substrate manufacturing process variations currently being evaluated to provide cost/time savings by reducing SiC interface requirements
  - CCOS processing of silicon clad SiC optics demonstrated to provide dramatic improvements in figure/finish achievable
    - Multiple off-axis aspheric optical elements demonstrated to have excellent surface figure quality and finishes suitable for stressing, high stray-light rejection earth observing telescope applications
  - CCOS process can be applied to optically figure CVD SiC claddings on reaction bonded SiC mirror substrates, providing further enhancement of surface quality to EUV quality
  - CCOS process modifications being demonstrated in order to support rapid optical polishing to complement rapid SiC mirror fabrication processes